Radiative charm decays and BSM physics

Svjetlana Fajfer
Physics Department, University of Ljubljana and Institute J. Stefan, Ljubljana, Slovenia

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Overview

• Motivation;
• SM in rare charm decays: $D \to V\gamma$; $D \to \pi \mu\mu$;
• From B anomalies to charm physics;
• Signatures of NP in charged current and FCNC charm decays;
• Dark Matter search in rare charm decays;
• Summary.
How about charm?

- In experiments producing B mesons there are always D mesons;
- Charm offers tests of possible NP in up sector at low-energies;
- If NP couples to weak doublets of quarks, CKM connects it with charm sector.
- Lattice QCD made progress for charm meson coupling constants and some form-factors.
- Can one see NP in charm decays not being present in B meson?
SM effective Hamiltonian for rare charm decays -FCNC

\[ \mathcal{H}_{\text{eff}} = \lambda_d \mathcal{H}_d + \lambda_s \mathcal{H}_s - \frac{4G_F \lambda_b}{\sqrt{2}} \sum_{i=3,\ldots,10,S,P,\ldots} C_i O_i \]

Tree-level 4-quark operators  (Short-distance) penguin operators

1) At scale \( m_W \) all penguin contributions vanish due to GIM;

2) SM contributions to \( C_{7,\ldots,10} \) at scale \( m_c \) entirely due to mixing of tree-level operators into penguin ones under QCD

3) SM values at \( m_c \)

\[ C_7 = 0.12, \quad C_9 = -0.41 \]

(recent results: de Boer, Hiller, 1510.00311, 1701.06392, De Boer et al, 1606.05521) 1707.00988 )

De Boer talk!
Effective Lagrangian

\[ \mathcal{L}_{\text{SD eff}} = \frac{G_F}{\sqrt{2}} V_{cb}^* V_{ub} \sum_{i=7,9,10} C_i Q_i \]

\[ Q_7 = \frac{e}{8\pi^2} m_c F_{\mu\nu} \bar{u} \sigma^{\mu\nu} (1 + \gamma_5) u, \]
\[ Q_9 = \frac{e^2}{16\pi^2} \bar{u}_L \gamma_\mu c_L \bar{\ell} \gamma^\mu \ell, \]
\[ Q_{10} = \frac{e^2}{16\pi^2} \bar{u}_L \gamma_\mu c_L \bar{\ell} \gamma^\mu \gamma_5 \ell, \]

Q_7 contributes to \( c \to u\gamma \) and \( c \to ul^+l^- \)

all three operators contribute to \( c \to ul^+l^- \)

C. Greub et al., PLB 382 (1996) 415;

\[ BR(D \to X_u\gamma) \sim 10^{-8} \]
<table>
<thead>
<tr>
<th>Branching Ratio</th>
<th>$D^0 \to \rho^0 \gamma$</th>
<th>$D^0 \to \omega \gamma$</th>
<th>$D^0 \to \phi \gamma$</th>
<th>$D^0 \to \bar{K}^* \gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belle [24]$^\dagger$</td>
<td>$(1.77 \pm 0.31) \times 10^{-5}$</td>
<td>–</td>
<td>$(2.76 \pm 0.21) \times 10^{-5}$</td>
<td>$(4.66 \pm 0.30) \times 10^{-4}$</td>
</tr>
<tr>
<td>BaBar [33]$^\dagger$</td>
<td>–</td>
<td>–</td>
<td>$(2.81 \pm 0.41) \times 10^{-5}$</td>
<td>$(3.31 \pm 0.34) \times 10^{-4}$</td>
</tr>
<tr>
<td>CLEO [34]</td>
<td>–</td>
<td>$&lt; 2.4 \times 10^{-4}$</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

Note: all SM Th predictions for $\text{BR}(D^0 \to \rho^0 \gamma)$ smaller than exp. rate!

Recent work: Hiller & De Boer 1701.06392

Talk of De Boer at CKM 2018 on 20 Sept.!
New Physics in charm processes

Constraints from K, B physics

Constraints from EW physics, oblique corrections, $Z \rightarrow b \bar{b}$

Constraints from LHC

NP in charm

For example

$$L_{eff} = \frac{4G_F}{\sqrt{2}} \bar{Q}_{Li} \gamma_\mu Q_{Lk} \bar{l}_{Ln} \gamma^\mu l_{Lm}$$

Up quark in weak doublet “talks” to down quark via CKM!

Effects of NP in charm suppressed by $V_{cb}^* V_{ub}$. 

$Q_{iL} = \begin{bmatrix} V_{* i l} u_j \\ d_i \end{bmatrix}$
Models of NP explaining B anomalies

<table>
<thead>
<tr>
<th>Spin</th>
<th>Color singlet</th>
<th>Color triplet</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>2HDM</td>
<td>Scalar LQ</td>
</tr>
<tr>
<td></td>
<td></td>
<td>R parity - sbottom</td>
</tr>
<tr>
<td>1</td>
<td>W', Z'</td>
<td>Vector LQ</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Dark matter?</td>
</tr>
</tbody>
</table>

2HDMII cannot explain $R_{D(*)}$

New gauge bosons, $W'$, $Z'$ - difficult to construct UV complete theory

Leptoquarks?

Nature of anomaly requires NP in quark and lepton sector!
It seems that LQs are ideal candidates to explain all B anomalies at tree level!

- Is charm physics sensitive on NP explaining B puzzles?
- Can some NP be present in charm and not in beauty mesons?
Leptoquarks as a resolution of B anomalies:

\[ \text{LQ} = (\text{SU}(3)_c, \text{SU}(2)_L, Y) \]

or \[ \text{LQ} = (\text{SU}(3)_c, \text{SU}(2)_L, Y) \]

\[ \text{Q} = I_3 + Y \]

<table>
<thead>
<tr>
<th>Model</th>
<th>( R_D(*) )</th>
<th>( R_K(*) )</th>
<th>( R_D(<em>) \ &amp; \ R_K(</em>) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( S_1 = (\bar{3}, 1)_{1/3} )</td>
<td>✓</td>
<td>✗</td>
<td>✗</td>
</tr>
<tr>
<td>( R_2 = (3, 2)_{7/6} )</td>
<td>✓</td>
<td>✗*</td>
<td>✗</td>
</tr>
<tr>
<td>( S_3 = (\bar{3}, 3)_{1/3} )</td>
<td>✗</td>
<td>✓</td>
<td>✗</td>
</tr>
<tr>
<td>( U_1 = (3, 1)_{2/3} )</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>( V_2 = (3, 1)_{2/3} )</td>
<td>✗</td>
<td>✗</td>
<td>✗</td>
</tr>
<tr>
<td>( \bar{V}<em>2 = (\bar{3}, 2)</em>{-1/6} )</td>
<td>✗</td>
<td>✗</td>
<td>✗</td>
</tr>
<tr>
<td>( U_3 = (3, 3)_{2/3} )</td>
<td>✗</td>
<td>✓</td>
<td>✗</td>
</tr>
</tbody>
</table>

No single scalar LQ to solve simultaneously both anomalies!

Scalar LQ simpler UV completion;

Only \( R_2 \) and \( S_1 \) might explain \( (g-2)_\mu \) (both chiralities are required with the enhancement factor \( m_t/m_\mu \)) Muller 1801.0338.

Doršner, SF, Greljo, Kamenik, Košnik, 1603.04993

S.Fajfer, Tau 2018
LQ and charm charged current

Triplet LQ $S_3$ in charm leptonic decays decay

$$\mathcal{L}_{\bar{u}^i d^j \ell \nu_k} = -\frac{4G_F}{\sqrt{2}} \left[ (V_{ij} U_{\ell k} + g_{ij;\ell k})(\bar{u}^i_L \gamma^\mu d^j_L)(\bar{\ell}_L \gamma^\mu \nu^k_L) \right] .$$

Test of lepton flavour universality (LFU)

$$\frac{R_{\tau,\mu}^{C,LQ}}{R_{\tau,\mu}^{C,SM}} = \left[ 1 - \frac{\nu^2}{2m_{S_3}^2} ( (V y_3^*)_{s\tau} (y_3^*)_{s\tau} - V y_3^*)_{s\mu} (y_3^*)_{s\mu} \right] .$$

Comes from the fit of $R_{K(*)}$ with $S_3$

Doršner, SF, Greljo, Kamenik Košnik, 1603.04993;
Scalar or tensor currents

\[ \mathcal{L}_{\text{eff}} = -\frac{4 G_F}{\sqrt{2}} V_{cq} \left[ g_S(\mu) (\bar{c}_R q_L)(\bar{\ell}_R \nu_L) + g_T(\mu) (\bar{c}_R \sigma_{\mu\nu} q_L)(\bar{\ell}_R \sigma^{\mu\nu} \nu_L) \right], \]

\[ \mathcal{B}(D_s \to \tau \nu) = \tau_{D_s} \frac{m_{D_s} m_{\tau}^2 G_F^2 |V_{cq}|^2}{8\pi} \left(1 - \frac{m_{\tau}^2}{m_{D_s}^2}\right)^2 |1 + \frac{m_{D_s}^2}{m_\tau (m_c + m_s)} g_S|^2 \]

Scalar leptogquarks \( \tilde{R}_2(3, 2, 1/6) \), \( R_2(3, 2, 7/6) \) can produce scalar and tensor couplings

\[ \mathcal{L}_{R_2} = (V g_R)_{ij} \bar{u}^i P_R e^j R_2^{5/3} + (g_R)_{ij} \bar{d}^i P_R e^j R_2^{2/3} \]

\[ + (g_L)_{ij} \bar{u}^i P_L \nu^j R_2^{2/3} - (g_L)_{ij} \bar{u}^i P_L e^j R_2^{5/3} + \text{h.c.} \]

In B physics branching ratio \( B \ (Bc) \to \tau \nu \) very constraining for NP!

In explaining B anomalies couplings present in rare D do not appear. One can make full low-energy study, without B mesons as done in 0906.5585 and exclude, it by the bounds from

\[ D^0 \to \mu^+ \mu^- , \ D_s \to \mu \nu , \ D \to \mu \nu , \ K_L \to \mu^+ \mu^- \]
Leptoquarks in $c \to u\gamma$

Constraints from

$c^- \to \pi^- \nu_\tau$

$c^- \to K^- \nu_\tau$

$\Delta m_D$

$D^+ \to \tau^+ \nu_\tau$

$D_s^+ \to \tau^+ \nu_\tau$

$K^+ \to \pi^+ \nu\bar{\nu}$

Even for $\tau$ in the loop too small contribution!

Masses of $m_{LQ} \approx 1$ TeV.

Within LQ models the $c \to u\gamma$ branching ratios are SM-like with CP asymmetries at $O(0.01)$ for $S_{1,2}$ and $V_{-2}$ and SM-like for $S_3$. Vector LQ $V_{-1} A_{CP} \sim O(10\%)$. The largest effects arise from $\tau$-loops.

$S_3$ can explain $R_{K(*)}$!
CP asymmetry in charm radiative decays

\[ A_{CP}(D \rightarrow V\gamma) = \frac{\Gamma(D \rightarrow V\gamma) - \Gamma(\bar{D} \rightarrow \bar{V}\gamma)}{\Gamma(D \rightarrow V\gamma) + \Gamma(\bar{D} \rightarrow \bar{V}\gamma)} \]

\[ |A_{CP}^{SM}| < 2 \cdot 10^{-3} \]

Belle, 1603.03257

LQs give as large contributions as SM

\[ A_{CP}(D^0 \rightarrow \rho^0\gamma) = 0.056 \pm 0.152 \pm 0.006 \]

\[ A_{CP}(D^0 \rightarrow \phi\gamma) = -0.094 \pm 0.066 \pm 0.001 \]

\[ A_{CP}(D^0 \rightarrow \bar{K}^*0\gamma) = -0.003 \pm 0.020 \pm 0.000 \]
$D^0 \rightarrow \mu^+ \mu^-$

Most general dimension 6 effective Lagrangian for $c \rightarrow ul^+l^-$

\[
\mathcal{O}_7 = \frac{e m_c}{(4\pi)^2} (\bar{u} \sigma_{\mu\nu} P_R c) F^{\mu\nu}, \\
\mathcal{O}_9 = \frac{e^2}{(4\pi)^2} (\bar{u} \gamma^\mu P_L c)(\bar{\ell} \gamma_\mu \ell), \\
\mathcal{O}_{10} = \frac{e^2}{(4\pi)^2} (\bar{u} \gamma^\mu P_L c)(\bar{\ell} \gamma_{\mu\gamma_5} \ell), \\
\mathcal{O}_S = \frac{e^2}{(4\pi)^2} (\bar{u} P_R c)(\bar{\ell} \ell), \\
\mathcal{O}_P = \frac{e^2}{(4\pi)^2} (\bar{u} P_R c)(\bar{\ell} \gamma_{5\ell}), \\
\mathcal{O}_T = \frac{e^2}{(4\pi)^2} (\bar{u} \sigma_{\mu\nu} c)(\bar{\ell} \sigma^{\mu\nu} \ell), \\
\mathcal{O}_{T5} = \frac{e^2}{(4\pi)^2} (\bar{u} \sigma_{\mu\nu} c)(\bar{\ell} \sigma^{\mu\nu} \gamma_{5\ell})
\]

SF, N. Kosnik, 1510.00965

LHCb bound, 1305.5059

$\mathcal{B}(D^0 \rightarrow \mu^+ \mu^-) < 6.2 \cdot 10^{-9}$ at CL=90%

Helicity suppressed decay!

$|C_S - C'_S|^2 + |C_P - C'_P + 0.1(C_{10} - C'_{10})|^2 \lesssim 0.007$

Fajfer CKM 2018
SM prediction: Long distance contributions most important! peaks at $\rho, \omega, \phi$ and $\eta$ resonances

$$D \to \pi V \to \pi l^+ l^-$$

de Boer, Hiller, 1510.00311, SF and Kosnik, 1510.00965

LHCb bound- assumption – constant amplitude
LHCb 1304.6365

(SF and Kosnik, 1510.00965)
Maximally allowed values of the Wilson coefficients in the low and high energy bins according to LHCb 1304.6365:

\[
\begin{align*}
\text{BR}(\pi^+\mu^+\mu^-)_I &\equiv \text{BR}(D^+ \rightarrow \pi^+\mu^+\mu^-)_{q^2\in[0.0625,0.276]\ \text{GeV}^2 < 2.5 \times 10^{-8}} \\
\text{BR}(\pi^+\mu^+\mu^-)_{II} &\equiv \text{BR}(D^+ \rightarrow \pi^+\mu^+\mu^-)_{q^2\in[1.56,4.00]\ \text{GeV}^2 < 2.9 \times 10^{-8}}
\end{align*}
\]
\[ A_{FB}(q^2) \equiv \left( \int_0^1 - \int_{-1}^0 \right) \, d \cos \theta \frac{d \Gamma(D \rightarrow \pi \ell \ell)}{dq^2 \, d \cos \theta} \]

\[ = \frac{b_\ell(q^2)}{a_\ell(q^2) + \frac{1}{3} c_\ell(q^2)} \]

Forward-backward asymmetry for the resonant background itself (orange) and in the scenario

\[ C_S = 0.049/\lambda_b \quad C_T = 0.2/\lambda_b \]
| $|\tilde{C}_i|$ | $|\tilde{C}_i|_{\text{max}}$ |
|----------------|----------------|
|                | $\text{BR}(\pi\mu\mu)_{I}$ | $\text{BR}(\pi\mu\mu)_{II}$ | $\text{BR}(D^0 \rightarrow \mu\mu)$ |
| $\tilde{C}_7$  | 2.4            | 1.6            | -               |
| $\tilde{C}_9$  | 2.1            | 1.3            | -               |
| $\tilde{C}_{10}$ | 1.4          | 0.92           | 0.63           |
| $\tilde{C}_S$  | 4.5            | 0.38           | 0.049          |
| $\tilde{C}_P$  | 3.6            | 0.37           | 0.049          |
| $\tilde{C}_T$  | 4.1            | 0.76           | -              |
| $\tilde{C}_{T5}$ | 4.4        | 0.74           | -              |
| $\tilde{C}_9 = \pm \tilde{C}_{10}$ | 1.3            | 0.81           | 0.63           |

Best bounds from $D^0 \rightarrow \mu^+\mu^-$

$|\tilde{C}_i| = |V_{ub}V_{cb}^* C_i|$

region I

$q^2 \in [0.0625, 0.276] \text{ GeV}^2$

region II

$q^2 \in [1.56, 4.00] \text{ GeV}^2$

$\text{BR}(D^0 \rightarrow \mu^+\mu^-) < 7.6 \times 10^{-9}$
For the transitions \( q_0 C C P \) and \( D \) are hindered. New physics models which fulfill this condition are main candidates to be exposed experimentally in the high dilepton invariant mass bin than in the low dilepton invariant mass bin, and this statement applies in the branching fraction of \( i \) branching fraction of \( \mu^+ \mu^- \) presented in Tab. 3. The LFU ratio \( C \) is negligible \( \mathcal{O}(10^{-2}) \). The strongest constraints on \( \mathcal{R} \) there can be NP contributions, similarly to what was assumed for the angular asymmetries puzzle, as presented in e.g. Ref. 5–5. We define LFU ratios in the low-dilepton invariant mass bin of \( \mathcal{O}(10^{-2}) \) at high dilepton invariant mass bin and maximal value of each Wilson coefficient describing \( \mathcal{O}(10^{-2}) \), while results in small \( \mathcal{O}(10^{-2}) \). This assumption leads to the same  

\[
R_{\pi}^{I,SM} = 0.87 \pm 0.09
\]

The disagreement between the measurement and the value \( \mathcal{O}(10^{-2}) \). The spread in these predictions is large because of unknown relative phases in the resonant part of the spectrum, i.e., Table III. The LFU ratio \( C \).

| \( |\tilde{C}_i|_{\text{max}} \) | \( R_{\pi}^{II} \) |
|----------------|------------------|
| SM             | -                | 0.999 \( \pm 0.001 \) |
| \( \tilde{C}_7 \) | 1.6              | \( \sim 6-100 \) |
| \( \tilde{C}_9 \) | 1.3              | \( \sim 6-120 \) |
| \( \tilde{C}_{10} \) | 0.63             | \( \sim 3-30 \) |
| \( \tilde{C}_S \) | 0.05             | \( \sim 1-2 \) |
| \( \tilde{C}_P \) | 0.05             | \( \sim 1-2 \) |
| \( \tilde{C}_T \) | 0.76             | \( \sim 6-70 \) |
| \( \tilde{C}_{T5} \) | 0.74             | \( \sim 6-60 \) |
| \( \tilde{C}_9 = \pm \tilde{C}_{10} \) | 0.63             | \( \sim 3-60 \) |
| \( \tilde{C}_{9}' = -\tilde{C}_{10}'|_{\text{LQ}(3,2,7/6)} \) | 0.34             | \( \sim 1-20 \) |

Assumptions:
- e^+e^- modes are SM-like;
- NP enters in \( \mu^+ \mu^- \) mode only;
- listed Wilson coefficients are maximally allowed by current LHCb data.
Scalar Leptoquarks \( (3,2,7/6) \) contributes to FCNC decay

\[
\mathcal{L}^{(5/3)} = (\bar{\ell}_R Y_L u_L) \Delta^{(5/3)*} - (\bar{u}_R Y_R \ell_L) \Delta^{(5/3)} + \text{h.c.}
\]

generates S, P, T, T_5, V and A

In the case of \( \Delta C = 2 \) in oscillation there is also a LQ contribution

\[
C_6(m_\Delta) = - \frac{(Y_{c\mu}^R Y_{u\mu}^R)^2}{64\pi^2 m_\Delta^2} = - \frac{(G_F \alpha)^2}{32\pi^4} m_\Delta^2 (\tilde{C}_9')^2
\]

\[
|C_6(m_\Delta)| < 2.5 \times 10^{-13} \text{ GeV}^{-2} \quad \implies \quad |\tilde{C}_9', \tilde{C}_{10}'| < 0.34
\]

Bound from \( \Delta C = 2 \) slightly stronger, but comparable to the bound coming from

\[
D^0 \rightarrow \mu^+ \mu^-
\]

\[
- \tilde{C}_{10}' = \tilde{C}_9' = 0.63 ,
\]

\[
4\tilde{C}_T = 4\tilde{C}_{T5} = \tilde{C}_P = \tilde{C}_S = -0.049
\]

at LQ mass scale

R_2 \ (3,2,7/6) can explain R_{D(*)} (D. Becirevic et al. 1806.05689)
Scalar Leptoquaks in charm FCNC processes

\[
\mathcal{L}_{\bar{c}_L u L} = -\frac{4G_F}{\sqrt{2}} \left[ c_{c u}^{LL} (\bar{c}_L \gamma^\mu u_L)(\bar{\ell}_L \gamma^\mu \ell_L) \right] + \text{h.c.},
\]

\[
C_{c u}^{LL} = -\frac{v^2}{2m_{S_3}^2} (V_{c s}^* g_{s \mu} + V_{c b}^* b_{b \mu}) (V_{u s} g_{s \mu} + V_{u b} b_{b \mu})
\]

\[C_{c u}^{LL} \] is 100 times smaller than current LHCb bound!

\[ (3,3,-1/3) \]

\[ (3,1,-1/3) \] introduced by Bauer and Neubert in 1511.01900 to explain both B anomalies. In 1608.07583, Becirevic et al., showed that model cannot survive flavor constraints:

\[
K \rightarrow \mu\nu, \quad B \rightarrow \tau\nu, \quad \tau \rightarrow \mu\gamma \quad \text{and} \quad D_s \rightarrow \tau\nu, \quad D \rightarrow \mu^+\mu^-
\]
Vector Leptoquark \((3,1,5/3)\)

not present in B physics at tree level! (for loop effects in B Camargo-Molina, Celis, Faroughy 1805.04917)

\[
\mathcal{L} = Y_{ij}(\bar{\ell}_i \gamma_\mu P_R u_j) V^{(5/3)\mu} + \text{h.c.} \\
C_9' = C_{10}' = \frac{\pi}{\sqrt{2} G_F \lambda_b \alpha} \frac{Y_{\mu c} Y_{\mu u}^*}{m_V^2} \\
D^0 - \bar{D}^0 \hspace{1cm} C_6(m_V) = \frac{(Y_{\mu u} Y_{\mu c}^*)^2}{32 \pi^2 m_V^2} = \frac{(G_F \alpha)^2}{16 \pi^4} m_V^2 (\tilde{C}_9')^2
\]

\[
|\tilde{C}_9', \tilde{C}_{10}'| < 0.24
\]

\[D \rightarrow \pi \mu^+ \mu^-\] In the high \(q^2\) region branching ratio is \(1.4 \times 10^{-8}\) two times smaller then the experimental bound
<table>
<thead>
<tr>
<th>Model</th>
<th>Effect</th>
<th>Size of the effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scalar leptoquark (3,2,7/6)</td>
<td>$C_S, C_P, C'<em>S, C'<em>P, C_T, C</em>{T5}$, $C_9, C</em>{10}, C'<em>9, C'</em>{10}$</td>
<td>$V_{cb} V_{ub}</td>
</tr>
<tr>
<td>Vector leptoquark (3,1,5/3)</td>
<td>$C'<em>9 = C'</em>{10}$</td>
<td>$V_{cb} V_{ub}</td>
</tr>
<tr>
<td>Two Higgs doublet Model type III</td>
<td>$C_S, C_P, C'_S, C'_P$</td>
<td>$V_{cb} V_{ub}</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$V_{cb} V_{ub}</td>
</tr>
<tr>
<td>Z' model</td>
<td>$C'<em>9, C'</em>{10}$</td>
<td>$V_{cb} V_{ub}</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$V_{cb} V_{ub}</td>
</tr>
</tbody>
</table>
Belle collaboration 1611.09455
BR(D^0 → invisible) < 9.4 \times 10^{-5}

SM: BR(D^0 → vv) = 1.1 \times 10^{-30}

Badin & Petrov 1005.1277 suggested to search for processes with missing energy \( E \) in

\[ D^0 \rightarrow \gamma E \]

could be SM neutrinos or DM!

Bhattacharya, Grant and Petrov 1809.04606

\[ \mathcal{B}(D \rightarrow invisibles) = \mathcal{B}(D \rightarrow \nu \bar{\nu}) + \mathcal{B}(D \rightarrow \nu \bar{\nu} + \nu \bar{\nu}) + ... \]

c instead of b

The SM contributions to invisible widths of heavy mesons \( \Gamma(D^0 \rightarrow \text{missing energy}) \) are completely dominated by the four-neutrino transitions \( D^0 \rightarrow \nu \bar{\nu} \nu \bar{\nu} \).

\[ \mathcal{B}(D^0 \rightarrow \nu \bar{\nu} \nu \bar{\nu}) = (2.96 \pm 0.39) \times 10^{-27} \]
**U(1)\textsubscript{X} dark sector**

Gauge group \( SU(3) \times SU(2) \times U(1)\gamma \times U(1)\textsubscript{X} \)

- Request anomalies cancelled:

\[
U(1)^3\textsubscript{X}, \ U(1)^2\textsubscript{X}U(1)\gamma, \ U(1)\times U(1)\gamma^2 \text{ and } SU(3)^2U(1)\times X
\]

- Higgs sector: 2 doublets, one singlet

\[
\phi_0 = \left( \frac{\phi_0^+}{v_0 + H_0 + i\chi_0} \right); \quad \phi_X = \left( \frac{\phi_X^+}{v_X + H_X + i\chi_X} \right); \quad s = \frac{v_s + H_s + i\chi_s}{\sqrt{2}}
\]

\[
v^2 \equiv (v_0^2 + v_X^2), \quad \bar{v}^2 \equiv (v_s^2 + v_X^2), \quad c_\beta^2 = \frac{v_X^2}{v^2}
\]

- Invisible fermions necessary for anomaly cancellation

\[
\mathcal{L} \rightarrow -Y_s \bar{\chi}_L \chi R S - Y_s^* \bar{\chi}_R \chi L s^*. 
\]
$A_\mu$ and $X_\mu$ mix via $\kappa$

$M^+ \rightarrow \mu^+ \ell^-$

Is it possible to search for decay

$D \rightarrow \mu X$

$X$ is SM $\nu_\mu$ + DM gauge boson $\rightarrow$

invisible fermions

Exp: $D \rightarrow \tau \bar{\nu}_\tau \rightarrow \mu \bar{\nu}_\mu \nu_\tau \bar{\nu}_\tau$

Difficult to differentiate
- There is a possibility that $X \rightarrow e^+e^-$
- Can one see it in the decays $P \rightarrow \mu \nu X \rightarrow \mu \nu e^+e^-$
- First one should calculate SM values

Thanks D. Melikhov for providing us with $\langle \gamma^* | J_\mu | D_s \rangle$
For certain choice of parameters, $M_X \approx 50$ MeV

Constraints from $(g-2)_\mu$ and trident production allow rather small mixing $\kappa \sim 10^{-4}$
Flavour anomalies generate $s\tau$, $b\tau$ and $c\tau$ relatively large couplings.

s quark pdf function for protons are $\sim 3$ times lagrer contribution then for b quark.

1706.07779, Doršner, SF, Faroughy, Košnik

$$\sigma_{s\bar{s}}(y_{st}) = 12.042 \ y_{st}^4 + 5.126 \ y_{st}^2,$$

$$\sigma_{s\bar{b}}(y_{st}, y_{b\tau}) = 12.568 \ y_{st}^2 y_{b\tau}^2,$$

$$\sigma_{b\bar{b}}(y_{b\tau}) = 3.199 \ y_{b\tau}^4 + 1.385 \ y_{b\tau}^2,$$

$$\sigma_{c\bar{c}, u\bar{u}, u\bar{c}}(y_{st}) = 3.987 \ y_{st}^4 - 5.189 \ y_{st}^2.$$
Summary

- New physics explaining B anomalies, give rather small effects in charge current transitions;

- FCNC transition small contribution of Leptoquarks in charm decays observables;

- Few proposals to test DM in charm physics;

- NP searches at LHC: charm quark important.
Thanks!
Lepton flavor violation

\[ c \rightarrow u \mu^\pm e^\mp \]

\[ \mathcal{L}_{\text{weak}}^{\text{eff}} (\mu \sim m_c) = \frac{4 G_F}{\sqrt{2}} \frac{\alpha e}{4\pi} \sum_i \left( K_i^{(e)} O_i^{(e)} + K_i^{(\mu)} O_i^{(\mu)} \right) \]

\[ O_9^{(e)} = (\bar{u} \gamma_\mu P_L c) (\bar{e} \gamma^\mu \mu) \quad \quad O_9^{(\mu)} = (\bar{u} \gamma_\mu P_L c) (\bar{\mu} \gamma^\mu e) \]

\[ BR(D^0 \rightarrow e^+ \mu^- + e^- \mu^+) < 2.6 \times 10^{-7} \]
\[ BR(D^+ \rightarrow \pi^+ e^+ \mu^-) < 2.9 \times 10^{-6} \]
\[ BR(D^+ \rightarrow \pi^+ e^- \mu^+) < 3.6 \times 10^{-6} \]

\[ |K_{S,P}^{(l)} - K_{S,P}^{(l)'l}| \lesssim 0.4 , \]
\[ |K_{9,10}^{(l)} - K_{9,10}^{(l)'l}| \lesssim 6 , \quad |K_{T,T5}^{(l)}| \lesssim 7 , \]

\[ l = e, \mu \]

\[ BR(D^0 \rightarrow e^\pm \tau^\mp) < 7 \times 10^{-15} \]
D^0 \to \phi \gamma \text{ or } D^0 \to K^{0*} \gamma \text{ decays (SM-dominated)}

\[ A_{L,R}^{SM}(\rho^0) = A_{L,R}(\bar{K}^{*0}) \times [\text{U-spin corrections}] \]

\[ D^0 \to \rho^0 \gamma \]

the photon polarization and therefore \( A_\Delta \) in \( D^0 \to \rho^0 (\to \pi^+ \pi^-) \gamma \) becomes a null test of the SM.

\[ \Lambda_c \to p \gamma \]

Hiller & de Boer 1701. 06392

\[ B(\Lambda_c \to p \gamma) \sim \mathcal{O}(10^{-5}) \]

If \( \Lambda_c \)-baryons are produced polarized, such as at the Z, angular asymmetries in \( \Lambda_c \to p \gamma \) can probe chirality-flipped contributions

\[ A^\gamma = -\frac{P_{\Lambda_c}}{2} \frac{1 - |r|^2}{1 + |r|^2} \]

\[ P_{\Lambda_c} = -0.44. \]
Angular distributions in $D \rightarrow P_1P_2 l^+l^-$

De Beor and Hiller, 1805.08516

Modes sensitive to NP

LHCb result (1707.08377)

$$B(D^0 \rightarrow \pi^+\pi^-\mu^+\mu^-)_{[0.565-0.950] \text{GeV}} = (40.6 \pm 5.7) \times 10^{-8},$$

$$B(D^0 \rightarrow \pi^+\pi^-\mu^+\mu^-)_{[0.950-1.100] \text{GeV}} = (45.4 \pm 5.9) \times 10^{-8},$$

$$B(D^0 \rightarrow K^+K^-\mu^+\mu^-)_{[>0.565] \text{GeV}} = (12.0 \pm 2.7) \times 10^{-8},$$

- study of angular distributions SM – null tests
- simpler then in B decays due to dominance of long distance physics (resonances)
- NP induced integrated CP asymmetries can reach few percent
- sensitive on $C_{10}^{(')}$

Tests of LFU

$$R_{P_1P_2}^{D} = \frac{\int_{q_{2 \text{min}}}^{q_{2 \text{max}}} dB/dq^2(D \rightarrow P_1P_2\mu^+\mu^-)}{\int_{q_{2 \text{min}}}^{q_{2 \text{max}}} dB/dq^2(D \rightarrow P_1P_2e^+e^-)}$$

$$R_{\pi\pi}^{D \text{SM}} = 1.00 \pm O(\%)$$

$$R_{K\bar{K}}^{D \text{SM}} = 1.00 \pm O(\%)$$

only upper limits exists